NLO QCD corrections to 4 b-quark production

Nicolas Greiner

University of Illinois at Urbana-Champaign

in collaboration with
A.Guffanti, J.P.Guillet, T.Reiter, J.Reuter

LoopFest IX, 06/21/2010

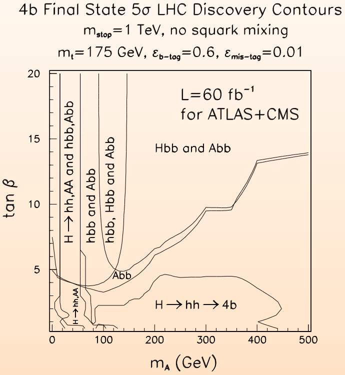
Outline

- **Motivation**
- $q\bar{q} \to 4b$
  - **Calculation**
  - **Results**
- **Outlook** $pp \to 4b$

Motivation

- NLO QCD corrections can lead to sizeable deviations from LO result.
  $\longrightarrow$ LO result often just rough estimate.
- NLO result reduces theoretical uncertainties. (scale dependence)
- Precision measurements require precise theoretical predictions for SM contribution.
- BSM models (SUSY) naturally have multiparticle final states.
- NLO (NNLO) result desirable for important processes.
  $2 \longrightarrow 4$ currently state of the art (NLO).
  $pp \longrightarrow t\bar{t}b\bar{b}$ [Bredenstein,Denner,Dittmaier,Pozzorini],[Bevilacqua,Czakon,Papadopoulos,Pittau,Worek]
  $pp \longrightarrow Wjjj$ [Berger et. al.],[Ellis,Melnikov,Zanderighi]
  $pp \longrightarrow t\bar{t}jj$ [Bevilacqua,Czakon,Papadopoulos,Worek]
  $pp \longrightarrow \gamma/Zjjj$ [Berger,Bern,Dixon,Febres Cordero,Ford,Gleisberg,Ita,Kosower,Maitre]

Motivation



[Dai,Gunion,Vega]

- For certain MSSM scenarios: $H \to b\bar{b}b\bar{b}$ enhanced.
- maybe the only discovery channel
- also important for other BSM scenarios
- important to know SM background
- added to Les Houches wish list

Calculation

$$\underline{pp \to 4b \ + X}$$

$$\left.\begin{array}{ll} LO: & q\,\bar{q} \to 4b \\ & g\,g \to 4b \end{array}\right\} \text{Virtual corrections.}$$

$$\left.\begin{array}{ll} NLO: & q\,\bar{q} \to 4b \ + g \\ & g\,g \to 4b \ + g \\ & q\,g \to 4b \ + q \end{array}\right\} \text{Real emission.}$$

Simplifications:

- b-quark massless
- neglect b-quark in initial state ($q \neq b$)
  Motivated by LHC kinematics and applied cuts.

$$q\bar{q} \to 4b \ + X$$ [Binoth,NG,Guffanti,Guillet,Reiter,Reuter]

$$\sigma_{NLO} = \int_{n+1} \left(d\sigma^R \quad - d\sigma^A \right) \quad + \int_n \left(d\sigma^B \quad + d\sigma^V \quad + \int_1 d\sigma^A \right)$$

2 independent calculations, both free of divergencies.

Virtual corrections: **GOLEM** [Binoth et. al]
Real emission and Born: **MadGraph** [Long,Stelzer], **Whizard** [Kilian,Ohl,Reuter]
Subtraction terms: **MadDipole** [Frederix,Gehrmann,NG], **Whizard**
Integration: **MadEvent** [Maltoni,Stelzer]

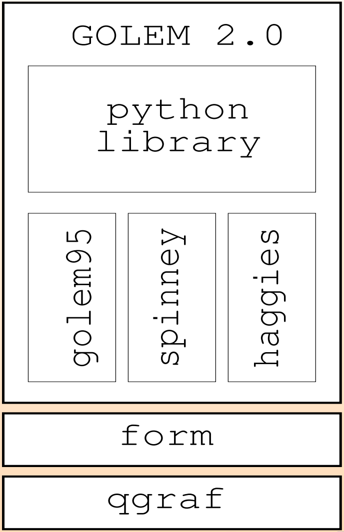
- All ingredients framework independent and stand alone applications.

Virtual corrections

General One Loop Evaluator for Matrix-Elements

- Based on Qgraf and Form
- Library for one-loop integrals (golem95)

  → T. Kleinschmidt's talk
- Matrix element generator for one-loop amplitudes
- Second, independent code based on FeynArts and FeynCalc for cross-checks



Subtraction terms

MadDipole : Package that automatically generates subtraction terms ($d\sigma^A$) and integrated subtraction terms ($\int_1 d\sigma^A$) in form of Catani-Seymour dipoles. (Color and helicity summed)

User: specify the NLO process
MadDipole: returns Fortran code for all necessary terms.

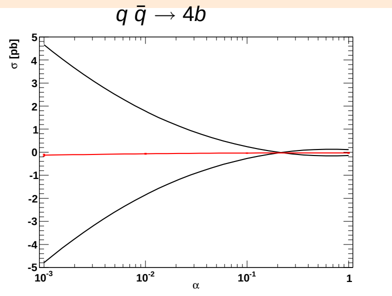
- unintegrated subtr. terms
- integrated terms: finite terms + coeff. of pole terms
- provides consistent calls of pdfs and cuts.

Several checks
– Second implementation in Whizard.
– Check against MCFM.
– Varying the cut-parameter α of subtraction terms provides powerful checks on many levels.

- Subtraction terms are only needed near singularity
  $\rightarrow$ Cut away parts of phase space where there is no sing.
- Introduce parameter α: $\mathcal{D}_{ij} \rightarrow \mathcal{D}_{ij}\theta(\alpha > s_{ij})$ [Nagy,Trocsanyi]

Integrated subtraction terms also depend on α, total result however independent:

$$\int_{n+1}\left(d\sigma^R - d\sigma^A\right) + \int_n \text{(finite parts of int. dip.)} = \text{const}$$



Phase space integration

Numerical phase space integration done using MadEvent where GOLEM- and MadDipole-code has been plugged in.

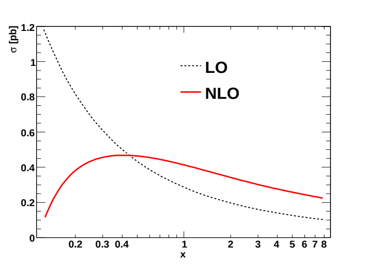
- Sanity checks of correct interplay virtual $\leftrightarrow$ reals by comparing Born and coefficients of $1/\epsilon$- and $1/\epsilon^2$-terms.
- Born cross section checked with Whizard.
- Calculation done using 't Hooft-Veltman- and $\overline{MS}$-scheme.
- Cut parameter set to $\alpha = 10^{-2}$.
  $\longrightarrow$ Leads to increase of speed and stability of integration.
- Used $3 \cdot 10^8$ points for real emission, $1.2 \cdot 10^6$ for virtuals, parallelized in 30/60 runs.
- CPU time per ps point: $\sim 5ms$ for reals, $\sim 4s$ for virtuals.

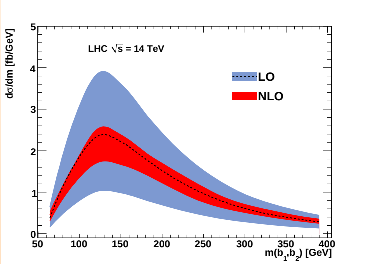
Imposed cuts:

- K_T-algorithm with $R = 0.8$.
- $P_T \geq 30$ GeV, $|\eta| \leq 2.5$ $\Delta R > 0.8$.

Renormalization scale: $\mu_R = x \cdot \mu_0, \quad \mu_0 = \sqrt{\sum_i P^2_{T,i}}$

Factorization scale: $\mu_F = 100\text{GeV}.$





$$\mu_0/4 \leq \mu_R \leq 2\mu_0$$

Scattering AMplitudes from Unitary-based Reduction Algorithm at the Integrand-level

[Mastrolia,Ossola,Reiter,Tramontano]

$\rightarrow$ G.Ossola's talk

2. approach: Making use of SAMURAI package to calculate virtuals for $q\bar{q} \rightarrow b\bar{b}b\bar{b}$.

Idea: Performing reduction on integrand level using OPP-method [Ossola,Papadopoulos,Pittau] in automated way.

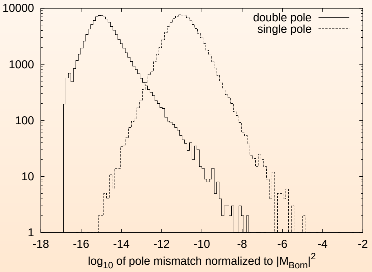
Results:

- Increase of speed ($\sim 0.4s$) per point
- Reduction of size of code by factor ~ 10
- Increased numerical stability

Numerical cancellation of singularities

Pole cancellations important check for numerical stability

$$\frac{\frac{Pole_{virt}}{Pole_{sub}} - 1}{|\mathcal{M}_{Born}|^2}$$



- Integration of $q\bar{q} \to b\bar{b}b\bar{b}$ with 10^5 points in double precision, cuts as before.
- No points with numerical problems found (large K-factor).

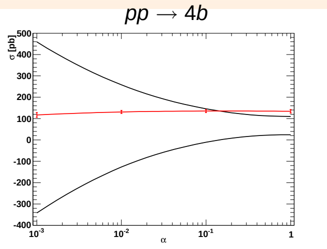
$\Rightarrow$ Numerical stability well under control.

Outlook

$$\underline{pp \longrightarrow 4b + X}$$

Real emission part:

- Implementation with MadGraph/Dipole/Event finished and integration working.



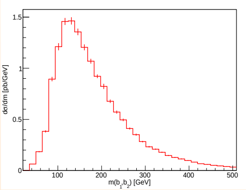
- CPU-time for real emission: $\sim$ 20ms per phase space point.
- Integration checked with with HELAC/PHEGAS.

Results for real emission $pp \to b\bar{b}b\bar{b} + X$

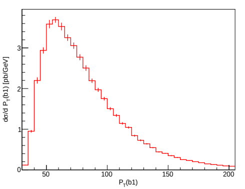
$|\mathcal{M}_{real}|^2$ - sub. terms.

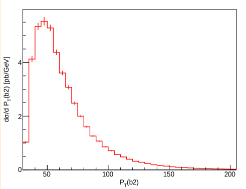
- Cuts as for $q\bar{q}$
- $\mu_r = \mu_F = \mu_0$
- $\alpha = 10^{-2}$
- 10^9 phase space points, splitted in 50 runs.
- jets ordered according P_T.

Invariant mass distribution.



P_T-distribution





Virtual part:

- Working on comparison with second independent code.
- Optimistic concerning size of code and CPU time.

Possible improvements:

- Instead of numerical integration take sample of unweighted events of the Born and perform reweighting with virtual corrections.
  $\longrightarrow$ Faster because less points needed.

Summary

- NLO QCD correction necessary for multi-leg final states at LHC
- Production of 4 b quarks important signal for MSSM/Higgs.
- Both virtual corrections and real emission / subtraction terms done in two different ways.
- Quark initiated case finished.
- Inclusion of SAMURAI lead to increase of speed and stability.
- For full $pp \longrightarrow 4b$ real emission finished and integration working.
  Further testing for virtual gg amplitude required.

Backup slides

P_T-distribution for 3. and 4. jet